Workshop Report:

Multi-Sectoral Urban Interactions: Fundamental Science Needs to Inform Pathways to More Resilient Communities in a Changing Climate

Organized by Christa Brelsford and Andrew Jones

A workshop organized by the MultiSector Dynamics Community of Practice Working Group on Urban Systems

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Synthesis of Key Findings

Human-Centric Research Perspectives are Needed to Understand Critical System Interactions, Uncertainties, and Outcomes Across Communities

- We need to broaden our research perspective from a top-down view to also include human-centric approaches. This requires understanding local determinants of outcomes and experiences and their dependencies on numerous interacting sectors.

- Measurement at human-centric scales is now possible because the digital data explosion enables near-real-time estimates of local scale, high frequency, stochastic indicators of weather, environmental conditions, infrastructure capacity and response, and socio-economic and behavioral patterns.

- We need analyses of the mechanisms through which co-evolving sectoral processes in cities lead to differential impacts across social groups and changes in urban resilience and vulnerability.

- Co-production with urban stakeholders is critical to ensure decision-relevant science. This is needed so that key processes in the systems and sectors of interest to stakeholders are incorporated into scientific scope and so that the research community can benefit from local knowledge, understanding, perspectives on issues of critical local concern, and community-based solutions.

- There are significant structural impediments to knowledge co-production; research that aims to advance equity and environmental justice goals in urban contexts must develop strategies to cope with these structural impediments.

Digital Trace Data Explosion Enables Transformative Human-Centric Research

- The recent explosion in digital trace data available about human behavior, mobility, and social processes is a transformative opportunity – for understanding fundamental characteristics of anthropogenic processes; for measuring and understanding inequality and its determinants; and for policymakers to understand what cities can do to mitigate and adapt to climate change on decision-relevant timescales.

- We need investment in data validation and comparison to infer representative real-world metrics from digital traces of anthropogenic processes. This requires rich computational methods – Bayesian data assimilation, anomaly detection, and statistical and machine learning.

- Machine learning models are a powerful strategy both for arriving at complex decisions with the help of massive and heterogeneous datasets and for predictive forecasting in decision support for future urban scenarios.

- If the data management infrastructure can be streamlined and scaled, observations and insights would be available for research and policy in a near-real-time manner.

Understanding Urban Resilience Requires New Theory, Observations, and Modeling that Integrates Human and Natural Systems

- Hazard-related risk is a function of environmental conditions as well as system-level interactions among infrastructural, behavioral, and institutional factors. Understanding how these factors interact to mitigate or enhance risk is a critical area of research requiring new theoretical frameworks, observations, and modeling.

- Beyond vulnerability assessment, decision-makers need insight into the multi-objective trade-offs among alternative adaptation strategies. This requires scientific foresight regarding the implications of hypothetical investment decisions, management changes, and/or environmental changes that may be out-of-sample with respect to past observed experience.

- In particular, green infrastructure and nature-based solutions can complement engineered infrastructure to enhance resilience and reduce urban emissions. Research is needed to understand how these investments function and at what scale they can be implemented.

- The physical characteristics of environmental extremes can be modified by the built environment within urban areas. This highlights the importance of two-way coupling among natural and human processes in urban areas.

Cities are Concentrators of Complex, MultiSectoral Interactions

- Examining how hazards propagate through urban systems is a useful way to understand coupled system behavior, including interactions across multiple scales and sectors, tipping points, differential harm, and adaptive responses.

- The heterogeneity of urban geographies and communities has implications for differential outcomes as well as key processes that play out at fine geographic and social scales. Determining which outcomes and processes require highly resolved data and modeling methods is important for guiding scientific investments.

- The capacity to generalize knowledge from one case study to other cities and regions is underdeveloped. Research on urban systems requires both depth that accounts for locally specific conditions and breadth that enables comparative evaluation across regions.

Section 1: Introduction

1a: Workshop Motivation

Urban areas and the supply networks that support their resource use are inherently Multi Sectoral systems composed of infrastructural, environmental, and socio-institutional components. These systems are vulnerable to accelerating and interacting stresses from climate change, population growth, resource scarcity, and land-use pressure at the same time as they have a major influence on regional and global systems. For instance, a majority of the world's greenhouse gas emissions, food consumption, and economic activity can be attributed to urban areas. Urban areas are highly heterogeneous, both across and within cities in terms of their socio-demographic, environmental, and infrastructural characteristics. This heterogeneity shapes how urban systems interact and co-evolve and contribute to different economic, environmental, and health outcomes for communities within urban areas. Urban heterogeneity also generates differential vulnerabilities to stressors and differential capacity for adapting to change. The evolution of urban space is thus critical in shaping how human societies respond to global change as they seek to improve resilience to stressors, support prosperous and equitable communities, and use natural resources in a sustainable manner. Developing a fundamental scientific understanding of urban heterogeneity and system interactions across sectors and scales is critical for mapping the resilience, sustainability, and equity implications of alternative future pathways.

Meanwhile, there is increasing recognition that urban systems are a key context for examining fundamental questions related to system dependencies, tipping points, and uncertainties. There is also a recognition that urban areas are a fruitful context to explore methodologies for model coupling across sectors and scales. Likewise, within the federal agencies such as the Department of Energy (DOE), there is increasing interest in developing shared modeling and data capabilities for understanding water- and energy-related challenges, many of which intersect with urban infrastructural, environmental, and social systems. However, efforts to coordinate among research groups and combine multi sector urban tools and insights to examine key uncertainties, interactions, and trade-offs are still nascent.

While social, ecological, and engineering domain-centered research is critically important, this siloing has the potential to lead to incomplete solutions or unintended tradeoffs. Making one part of an interconnected system more robust can introduce vulnerabilities elsewhere. Solutions that address only one system domain are unlikely to prove resilient in the future, under new and different stressors across these system domains.

1b: Workshop Objectives and Science Questions

The MultiSector Dynamics (MSD) Community of Practice is a multidisciplinary collective of researchers based at universities and national labs across the United States that aims to improve our understanding of the co-evolution of human and natural systems over time, and build the next generation of tools that bridge across sectors (energy, water, land, economy) and scales (spatial, temporal), and offer a holistic view of systems-of-systems.

The MSD Urban Systems Working Group organized this workshop to provide a venue for coordination and identification of shared objectives, research themes, and major knowledge gaps, as well as developing a shared strategy for addressing those gaps.

Overarching science questions that motivated the workshop are:

- What are the risks and trade-offs faced by the world's urban areas as they seek to increase resilience to changing stressors and balance multiple objectives such as human health, economic development, and sustainable use of energy, water, and land resources?
- How does urban change influence larger-scale infrastructure, economic, and Earth system processes, and how is urban evolution constrained by these larger systems?
- What role does social, environmental, and infrastructural heterogeneity within urban areas play in shaping evolutionary dynamics, and what are the implications of this heterogeneity for outcomes related to environmental justice?
- Which processes and couplings must be represented in conceptual frameworks, models, and data tools to rigorously understand multi-sector dynamics and the evolution of urban systems?

Key objectives were to:

- Foster shared understanding and lay the groundwork for collaboration among urban researchers across disciplines.
- Identify synergies across existing tools, models, and analytic capabilities.
- Identify critical knowledge gaps and high-priority research topics for moving the community forward that are particularly focused on identifying where the DOE's historical strengths in Earth system observation, model-data fusion, climate modeling, human-Earth interactions, high-performance computing, population demographics, and infrastructure modeling can contribute to the fundamental science needs for urban research.

1c: Workshop Structure and Participation

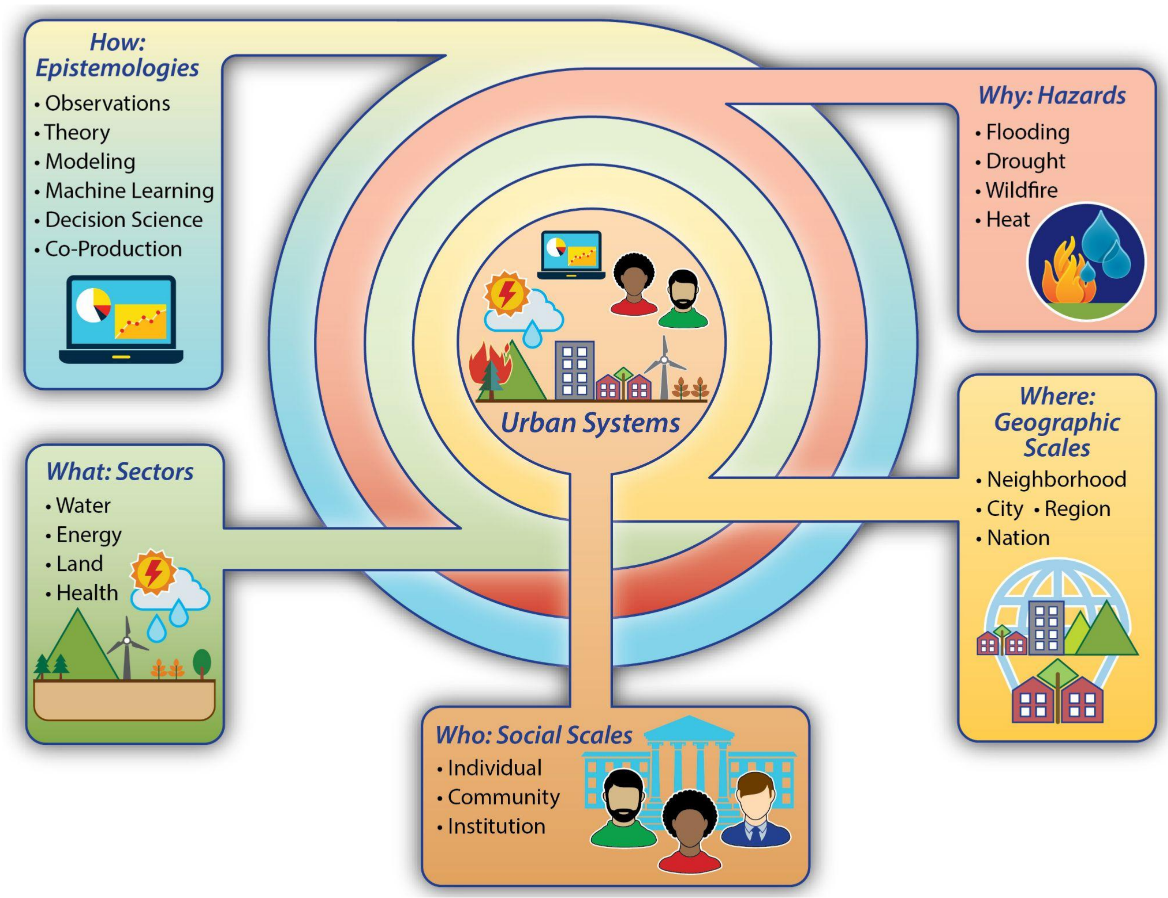

Figure 1: A conceptual diagram demonstrating multiple lenses that can be used for organizing the complexity of urban systems and scientific research on urban systems. In the center, environmental, social, and built systems processes interact to produce outcomes of relevance to resilience, equity, and sustainable use of resources. Moving outward, lived experiences and decision-making take place on a continuum of social scales from individual to institutional. Key process interactions and heterogeneities differ across spatial scales from neighborhoods to nations. Sectors connect people and resources across urban landscapes and act as behavioral aggregators from smaller to larger scales through infrastructure networks and management institutions. Urban systems are embedded within larger environmental systems and are vulnerable to changing hazards, which motivates questions regarding resilience and adaptation and provides a lens through which to understand differential outcomes and interactions across sectors and scales. The outer circle highlights the ways that we create knowledge about urban systems. Scientific insight and data, in turn feedback to inform decision-making and behavior across the social scales highlighted in the center. Each of these lenses provides a useful perspective on urban systems, and each is incomplete on its own.

The workshop was held virtually on July 21st, 22nd, and 23rd, 2021 in coordination with the Snowmass Energy Modeling Forum, Oak Ridge National Laboratory, and Lawrence Berkeley National Laboratory.

On July 21st, we hosted an open invitation plenary session with presentations and a panel discussion by four leading urban scientists: Luis Bettencourt, Karen Seto, Anu Ramaswami, and Paul Waddell. July 22nd and 23rd consisted of themed, small group discussions organized around the idea of research 'fault lines' – different ways of organizing the complexity of urban systems through disciplinary, methodological, or sectoral perspectives. By acknowledging what is often implicit, we aimed to better address the interactions across different ways of understanding cities. This can create space for integration and fundamental insights into the systems, sectors, scales, and processes that cities are composed of. The four breakout sessions were organized around 1) earth system hazards, 2) social scales, 3) urban sectors and systems, and 4) research epistemologies and methodological strategies. Figure 1 highlights our vision for how these lenses interact and complement each other.

The keynote panel on July 21st had about 100 participants from 36 institutions including attendees from five DOE national laboratories, the DOE, and many universities. There were international participants from institutions in New Zealand, Germany, India, and the Netherlands.

The in-depth discussion sessions on July 22 and 23 had about 50 participants, also from a range of DOE national laboratories, universities, and international institutions. Nine participants attended from five minority serving institutions. Participants in these interactive sessions were about 30% women, and also included a large fraction of early-to-mid career researchers. A "speed networking" session provided a unique opportunity for informal conversation and building community in the virtual meeting format.

Section 2: Summary of Plenary Session

In the keynote panel on July 21st, Dr. Karen Seto highlighted that urbanization is sufficiently widespread and consequential that it can be considered a global change phenomenon. Dr. Seto highlighted that urbanization is central to many 21st century challenges, and because of its scope should be treated as an integral component of global change research. She emphasized that urban systems are missing from global scale coupled climate models and that the expected rapid pace of urbanization in the remainder of the 21st century provides a very significant opportunity for climate action. She highlighted five key knowledge gaps in our ability to measure and understand the role of urban spaces in the global climate system: particularly the importance of collecting and managing data measuring human activities and calling for the co-development of computational methods to analyze both quantitative and qualitative data, with top-down and bottom-up approaches. Finally, Dr. Seto concluded with a 'call to arms' for communities like this one to do the science that will contribute to knowledge and help policymakers understand what cities can do to mitigate and adapt to climate change.

Dr. Luís Bettencourt emphasized the role that cities play as concentrators of cross-sector dynamics, playing an outsize role in broader-scale changes. He argued that cities exist to solve a connectivity problem; they function by facilitating multisectoral cost-benefit trade-offs; and they create change by creating and communicating new information through innovation, long term economic growth, and human development. Dr. Bettencourt highlighted the role of urban science as integrating scales and disciplines. Dr. Bettencourt highlighted existing DOE strengths in computational modeling, especially that with an attention to optimization and resilience, and applied to the infrastructural context. He wondered, though, if these methods are appropriate to the goals for stable socioeconomic and environmental outcomes. He then proposed three research gaps: flipping urban resilience research perspectives from a top-down view to a human centric view, from detailed modeling to high-precision, real-time data, and from temporal averages to high frequency, stochastic indicators. Each of these gaps requires integrating research gaps across population sizes, geographies, and time.

Dr. Anu Ramaswami provided a vision for how to use multi-system system science to move towards equitable, net-zero carbon cities. She showed ways in which urban decarbonization is possible. Dr. Ramaswami demonstrated that knowledge co-production with cities is essential for identifying key decision points towards a net-zero future, and has important local benefits. She also emphasized that attention to within city heterogeneity is critical for urban decarbonization to be socially sustainable. She proposed a number of key knowledge gaps: transboundary and cross-sector linkages of both small and large-scale infrastructures, measuring equity across multiple sectors and scales, the impact of land use decisions on greenery, the impact of greenery on carbon sequestration, and the combined influence of urban form and greenery on building energy use.

Dr. Paul Waddell demonstrated mechanisms through which fine scale urban data, machine learning, and cross-sectoral modeling can better inform urban planning and design. He highlighted the significant advances in integrated Urban-Environmental modeling and planning that have occurred over the last 20 years: moving from conceptual behavioral models through urban microsimulation towards microdynamics, and the addition of uncertainty quantification to urban models. He discussed the addition of machine learning techniques to complement existing statistical models, and then discussed recent applications of dynamic microsimulation models for decision support in resilience planning in the context of climate change. Dr. Waddell concluded by highlighting an open source, collaboratively developed urban data science toolkit (https://github.com/UDST).

All four speakers highlighted the importance of multiscale perspectives in understanding cities and the opportunities for research that have been enabled by the recent explosion of data available about human behavior and social processes.

Section 3: Environmental Hazards Breakout

Environmental hazards such as flooding, drought, wildfire, and extreme heat are a source of disturbance and stress on urban systems that range in magnitude from economically disruptive inconveniences to dramatic cascading infrastructure failures with direct impacts on human health and well-being. As climate change alters the characteristics and frequency of such hazards, infrastructure systems and institutions that were built for another era must adapt in order to maintain or enhance resilience to these stressors. To complicate things further, the built environment itself can alter the characteristics of environmental extremes, for example through the urban heat island effect or through changes in surface hydrological properties.

Environmental extremes often do not impact just one sector, scale, or social group at a time. For instance, flooding can impact transportation, energy, and water infrastructure simultaneously. Extreme heat taxes the electricity grid, which has an exacerbating influence on health outcomes through the loss of air conditioning access. Moreover, environmental, infrastructural, and social heterogeneity leads to differential vulnerabilities and adaptive capacities across urban landscapes. As a result, communities experience and respond to hazards in different ways, reflecting and frequently reinforcing existing inequities.

Indeed what is understood to be a hazard is arguably as much a function of the sensitivity of our social and built systems to extreme conditions as the environmental conditions themselves. And while some individual built assets may have clearly defined environmental thresholds that trigger their failure, the conditions that lead to system-wide and cascading failures depend on the overall system configuration including the role of redundancy, heterogeneity, and adaptive behaviors.

Examining how hazards propagate through urban systems is a useful way to understand coupled system behavior, including critical linkages across scales and sectors and the role of tipping points, feedbacks, and adaptive responses. The complexity of urban systems and the by-definition rarity and high impact of extreme events make the study of hazards challenging. Yet this complexity shapes both the risks and opportunities for resilience within urban systems, so it is critical to understand in order to both inform the options for future urban development and to understand urban evolution in a more fundamental sense.

Participants in the environmental hazards breakout were tasked with taking a hazard-specific lens to examine the most pressing challenges faced by urban communities in maintaining resilience in the face of climate change. They were asked to examine:

- which sectors, systems, and groups of people are most vulnerable to these hazards
- how these hazards play out through multi-sectoral systems,
- how the built environment interacts with the environmental processes that generate the hazard,
- the options available to adapt and create more resilience to these stressors and any tradeoffs these measures might have

- the most pressing science gaps that must be filled to address the challenges identified above and any promising directions for filling those gaps

Several common themes emerged across the breakout groups including:

- What defines hazard risk is a function of social and infrastructural vulnerabilities in addition to environmental characteristics
- There is a need to understand the changing risks faced by existing urban systems given the changing characteristics of environmental hazards and existing vulnerabilities
- There is also a need to examine how risks would shift as a result of alternative future pathways and their multi-objective implications
- Post-event decision making is important for understanding transformative dynamics
- Knowledge and data are an important aspect of decision-making, and so observational systems and science are part of the dynamic system of adaptation
- While there is an opportunity for real-time data and modeling to inform adaptive responses, there can be a tension between developing tools for decision support vs. fundamental scientific understanding
- Co-production is a valuable process for ensuring relevance of science for decision-making and so that key processes are incorporated into scientific scope
- Understanding how case-specific insights scale across urban areas or across events is a cross-cutting challenge

3a: Extreme Heat

Extreme heat poses a major threat to human health as well as infrastructure systems such as the electricity grid. It also contributes to other hazards such as poor air quality, wildfires and increase in water temperature, posing additional threats. While these hazards make it crucial to understand the extent of the extreme events, there are various limitations associated with data and modeling that restrict a comprehensive evaluation of extreme heat hazards at urban scale. For instance, the weather stations that monitor air temperature in a city are still sparse and do not provide an estimate of citywide temperatures. Satellite-based land surface temperature data, which is not the best indicator for heat stress, has been increasingly used to understand urban heat intensity. Further, limited attention has been paid to humidity-driven exacerbation of extreme heat impacts. Modeling studies typically make simplifying assumptions regarding the representation of surfaces and vegetation at urban scales, but it is difficult to determine how important these assumptions are for accurately representing key outcomes of interest given a lack of data needed for model validation at fine scales. Furthermore, more research is needed to evaluate socioeconomic disparities and unequal exposure to heatwaves. However, the lack of data on air conditioning and indoor temperature present major gaps in evaluating these disparities. Overall, heat adaptation measures can play a key role in reducing extreme heat impacts. There is a need for improvements in both infrastructure and governance to support adaptation to extreme heat events.

3b: Drought

Access to water is a critical element of human existence and drought (the lack of water access) is a direct threat to that existence. However, droughts in the current world are hard to conceptualize for the average individual because of the disconnect between where water is actually resourced (e.g., distant mountains or lakes or from deep underground) and how people experience water (e.g., from the tap in their homes). This struggle to conceptualize drought is exacerbated by the physical scales involved. For example, a city that sources its water from the river running through the city center can be impacted by natural or human controlled events miles upstream. Even more dramatically, the existence of massive western water conveyance projects mean that many western residents' water availability is impacted by the climate a thousand miles and two mountain ranges away. These massive pieces of infrastructure were designed ~150 years ago under a different climate and with different values in mind. They are not equipped to respond to 21st century needs.

The positive news is that there are varied and complex ways in which drought issues could be addressed. However, these approaches require profound insight into the myriad of physical, social, and economic drivers of drought to be effectively implemented. Specifically, new regulatory and economic policies can facilitate changes in water resource management. New technologies in treatment and reuse can increase water supplies. New environmental science can help understand and predict changes in water availability, and new hard and soft infrastructure can be designed and built for better water management. These new approaches will need to be supported by new science. Some water measurements are simple and have been done for years. Others, like understanding municipal water loss, are highly complex. Similarly, understanding and predicting consumption patterns is a complex and likely data-driven problem where machine learning and AI could be impactful. Because of the clear complexity of drought and water resource management and allocation, solutions must come through a co-design and decision science approach.

3c: Flooding

Flooding poses a number of challenges for urban systems, particularly when compounded by additional, related extremes like debris flows. It poses a major threat to infrastructure and people, challenges stormwater management systems, and at minimum levels it is an urban nuisance that degrades quality of life. Urban infrastructure is often long-lived and, in many cases, what exists today is not built for today's weather and climate extremes. During flooding events, urban managers often face challenges keeping infrastructure functioning and may lack the data necessary to make informed decisions on when to shut down systems to mitigate public harm. Coordination across departments and sectors is another challenge. They may also face challenges communicating flood-related risks to the public, particularly given the vulnerability of communications infrastructure to flooding and the events that cause flooding. Following flooding events, there is often a lack of capacity to provide relief, and institutions and individuals may face challenges making informed post-event adaptation decisions for themselves.

Natural and built engineering controls, as well as government actions surrounding land-use, are promising strategies for urban flooding adaptation. Similarly, infrastructure improvements and new infrastructure should be built to standards that account for potential future changes in urban flooding and equity in design. Moreover, land use practices can be adapted to allow for intermittent flooding in some areas, representing a shift away from the “fail-safe” paradigm that informs much of present-day infrastructure design (Kim et al. 2019). However, many gaps exist that inhibit science-informed adaptation and decision-making. Particularly, coordinated, high temporal and spatial resolution datasets for meteorological variables like rainfall, runoff, and infiltration do not always exist for the study and modeling of urban flooding, and critical information on the infrastructure itself may be proprietary. Knowledge about existing constraints on building/adapting and the costs/benefits of doing so is also needed. Additionally, the co-production of science is necessary but inhibited by gaps in incentives and the slow nature of co-production activities. Finally, challenges may exist in the scalability of research on flooding adaptation between different urban areas.

3d: Wildfires and Smoke

Wildfires pose a direct threat to human and mental health through water pollution, air pollution, destruction or interruption of human infrastructure such as electrical grids, and introduction of lived-trauma experiences before, during, and after the fire. Additionally, wildfires pose a major threat to ecosystems, impacting watersheds on a continuum from groundwater through the atmosphere and potentially leading to new ecological system states.. Living with fire is the new normal in many urban systems, and to adapt, it is important to develop strategies to reduce the risk of fire at the wildland urban interface (WUI), including changing building codes, implementing forest management practices, developing research that utilizes direct observations on private and public property, and leverage knowledge from millennia of indigenous practices including cultural burning.

Many gaps exist related to observations. During fires, it is critical to have real time, spatially continuous observations to map fire propagation and predict risk. Historical and recent environmental observations to use as baseline pre-fire datasets (soils, water quality, forest structure, fuels) are almost non-existent, and to establish a wildfire research theme, investments are needed to gather spatially broad pre-fire datasets. Machine learning and modeling are promising tools to approach the science gaps in addition to data collection. Modeling of fire propagation from wind, ignition sources, incorporating the WUI into fire models, and using the rich, but localized dynamics of forest structure and fuels leads to three different classes of modeling: 1) real-time emergency response modeling, 2) modeling for scenario planning, risk mitigation, and adaptation under climate change, and 3) modeling for scientific discoveries related to the important role of fire in landscapes. All modeling in this sense can be developed in the traditional physically-based framework, or novel machine learning approaches. Multiple tensions and value-differences exist between the idea of using models as research tools for science, versus modeling for real-time decision support, protection, and emergency management. While the public is asking for real-time tools to address the immediate emergency related to evacuations and real-time updates on hazard progression, models are typically developed as research tools unfit for real-time, rapid-response use. Additionally, models have incredible uncertainty because of the lack of data, thus any potential for real-time decision-making will require spatially complete high-resolution datasets for all areas in fire-prone regions.

Section 4: Social Scales Breakout

We are accustomed to ideas of temporal and geographic scale. It is also sometimes useful to consider 'social scales,' referring to the approximate number of people and complexity of the organizational processes under observation. Different 'social scales' have unique dominant processes and characteristics, influence different aspects of an urban system, and are best understood using different methodological strategies. Elinor Ostrom highlights the role that interacting social scales play in hierarchical decision-making processes in "Understanding Institutional Diversity" (Ostrom 2005). At the individual scale, people generally make choices that take factors like the climate, local organizations' rules, state laws, and the built infrastructure as external constraints. At the next larger social scale, groups of people like firms, local governments, school boards, and community organizations make choices about the rules or laws in their operating spaces, and make investments in infrastructure which take into account the local and regional climate and weather patterns and take higher order choices - like applicable state or federal laws and policies - as external constraints when making those local investments. Ostrom calls this the scale of collective choice. At this scale, there are substantial hierarchies within institutions - from groups to departments to schools in a university, and local, regional, and state governance processes. Finally, even higher order social processes are focused on the rules under which collective choices are made - this 'constitutional choice' social scale includes things like the collective choice decision strategy: all the ways in which many opinions are combined into an outcome.

The science around people and human choices is most well-developed when looking at individuals and households - Ostrom's individual choice scale. These can explore the behavior of an individual in an exogenous social context, which may include things like transportation mode choice within an urban environment, energy use in buildings, or crop choices by farmers in a stationary climatic and economic context (Evans and Kelley 2004; Bünning, Sangi, and Müller 2017; Macal et al. 2018; Aziz et al. 2018; Tamburino, Di Baldassarre, and Vico 2020). An emerging science around individual behavior capitalizes on newly available mobility traces to define regularities in travel distances or mobility patterns (Alessandretti, Aslak, and Lehmann 2020; Schläpfer et al. 2021; Depersin and Barthelemy 2018; Pappalardo et al. 2015).

Interactions at the collective choice scale are both hard to model and important. We intuitively know that social decision-making processes are highly non-linear. This makes prediction hard. But collective behavior is not random – there are underlying patterns. Historically, we haven't had the data to even observe fundamental empirical regularities to be explained by theory. The data revolution that we're living through now may support a more empirical understanding of social processes that are more complex than individuals in an exogenous context, and less aggregated than averages at a national or citywide scale.

At the scale of nations, 'constitutional choice' decision processes highlight the complexity of managing coarse institutional decisions, and the effects this has on collective choices, and ultimately individual outcomes. Some research at the urban and national scale explores the systematic relationships between a broad set of socio-economic outcomes and infrastructure requirements across cities within nations, dependent on urban population.

In four breakout sessions, we explored:

- What are the **most pressing science questions** needed to think about how your favorite urban system or climate hazard interacts with the decision processes occurring at the city and regional social scale?
- What **data, analytical strategies, theories, and models** are needed to better understand interactions between urban systems, regions, and the larger Earth system?
- In what ways would better understanding processes at the city scale support urban resilience, especially considering **vulnerable and marginalized communities**?
- What role does social, environmental, and infrastructural heterogeneity within urban areas play in shaping **evolutionary dynamics (e.g. technology adoption)**, and what are the implications of this heterogeneity for **outcomes related to environmental justice**?

Research about the basic properties of human systems covers many of the same topics as research which is designed to support decision-maker efforts to influence human systems. However, not all research *about* humans is *for* humans. This misconception may be partially driven by the reality that the distance between fundamental research *about* humans and its applicability *for* our laws, technologies, and behavior is much smaller than it is for fundamental research on other topics. Nonetheless, the distinction is important. In urban contexts, basic research *about* humans is badly needed to understand the mechanisms through which different sectors interact and co-evolve, particularly in the context of anticipated climate hazards. Human capacity to proactively respond to threats we anticipate is unique among the sectors which influence the Earth system. This means that careful characterization of our threat-anticipation behavior (across a full range of social scales) is necessary to understand the functioning and behavior of urban MultiSectoral Dynamics. At the same time, scientific information and data are among the factors that influence our threat-anticipation and risk mitigation behaviors, so there is a role for fundamental science to both support and understand these processes.

4a: Individuals and Households

The individual and household scale allows a bottom-up perspective beginning with the "atomic" units of climate hazard impacts (people), from which one may consider cumulative impacts at successively larger scales. Individual and household choices influence resource demands that in turn impact the functioning of infrastructure systems: electricity grids, water supply networks, transportation and communication networks can all be stressed by individuals' behavioral adaptations to climate-driven hazards.

Underlying differences in adaptive capacity to hazards are cross-cutting questions about how people perceive risk and make choices (irrespective of the hazard or sector). For example, how do short-term versus long-term perceptions of risk vary? How does the way individuals think about pervasive forms of risk contrast with how they think about novel forms of risk? How does the experience of extreme events influence subsequent perceptions of risk and willingness to adopt new household measures or migrate? To what degree does information provided to individuals and households from varying sources such as official communication, community leaders, social media, and personal communication enable proactive vs. reactive measures?

Many of these questions are rooted in spatial heterogeneity across demographics, socioeconomic status, and social contact networks. Spatial and social heterogeneity can both facilitate and inhibit early and full adoption of adaptive behaviors and technology. For example, household technology choices can reveal trade-offs between mitigating risk and factors like the affordability of services, particularly in the context of energy poverty. Adoption of technologies and preventative practices like migration away from a hazard may be influenced by ties with others in one's immediate environment (family, neighbors).

To better understand these issues and develop intervention strategies for mitigating hazard impacts at the individual and household level, the climate research community could benefit from robust representations of social networks, more holistic data on household-level built environment characteristics (i.e., land-use/land cover, elevation, age of structure, HVAC technology, number of units, utility provision), survey-based measures of how perceptions and decision-making process changes pre- to post- experience of extreme events (both lived and witnessed remotely, e.g. through news outlets, social media), as well as how different physical settings and risk types (i.e., flood zones, wildland-urban interface) shape those perceptions.

4b: Communities and Neighborhoods

Communities are not merely collections of individuals. Social processes that occur at the community scale can have significant influences on community resilience and preparedness in the context of climate hazards and other adverse events. Schools, firms, and civic organizations build infrastructure, make decisions, and set policies which influence local vulnerability, influence the choices that individuals make, and provide a meaningful backstop for disaster preparedness. As highlighted in Bettencourt's keynote address, when formal infrastructure systems fail, it is most typically individuals and community groups who temporarily serve as backup infrastructure, seeking to minimize gaps in critical urban services.

In seeking to minimize harms from climate change, community and neighborhood organizations wrestle with challenges around access to knowledge that can be applied to the local context, and data at an appropriate scale. Community organizations do not always have the technical capacity, time, and expertise to infer how global or regional trends in some process might influence their local context, nor access to the science professionals who could perform that translational research. There is dramatic within-city heterogeneity in educational attainment and access, and so there is heterogeneity in local capacity to access and interpret scientific findings. This can impede local efforts to understand and mitigate potential climate consequences, particularly when they occur in the context of the many other stressors communities and neighborhoods also face.

The substantial difficulties that community groups and organizations face in accessing scientific information which is accurate, relevant, and addresses their local context and particular circumstances also impedes our broader understanding of the role that communities, groups, and neighborhoods play in shaping the overall anthropogenic response in the human-Earth system. The scale of collective response is partially dependent on the information that the group accesses. We lack a rich system of knowledge transfer between community-scale groups and Earth system researchers which could simultaneously improve local response capacity and increase our ability to understand drivers and determinants of the human system responses. This would thus strengthen our skill in human-Earth system prediction.

4c: Cities and Regions

The city and regional scale is where collective decision-making starts to have large implications for the social scales above and below, making urban and regional research heavily integrated with the processes of individuals, communities, and nations. Research questions at this scale must be contextualized by relationships and impacts to their sub-scales of communities and individuals as well as national social and climate processes and policies. An important consideration for any urban and regional scale-specific science question is integrated modeling across spatial scales. An example like Super Blocks (bigger than neighborhood, smaller than city) help illustrate this challenge, as Super Blocks exist at community scales but create measurable changes in regional transportation patterns and impact policies around resource allocation. Many other relevant ongoing scientific questions consider planned migration in response to climate change. This will create large changes in city/regional population, adding stress to infrastructure, altering resource demand, and changing mobility patterns. An important consideration in response to modeling efforts should consider the opportunity for improving environmental justice outcomes. Lastly, many ongoing research agendas have a deep focus on urban processes, but there is a gap in knowledge between the evolving dynamics of urban and rural reliance. Scaling the knowledge transfer from one case study to other cities and regions is an underdeveloped research area and will be important.

To develop strategies for reducing adverse climate impacts at city and regional scales, we need to better understand *how* to use/interpret data/models for policy purposes. This will likely be more impactful than simply the creation and curation of *more data*. We need better evaluations for the fitness for purpose of models and understand what tools/models/data are appropriate for different purposes as transdisciplinary gaps still exist. Barriers created by disciplinary silos make informed decision-making extremely difficult. This leads to scenarios where cities and regions are forced to be reactive to hazards. How do we become proactive? Particularly with resource allocation between cities and to cities that are more vulnerable. How do these resource needs change over time particularly with environmental justice considerations?

4d: Nation to World

Social scales framing at national and global scales depends on the research objectives and topics, model, and data. Modeling the urban system and climate hazard interactions at national and global social scales is challenging due to the absence of urban representations in most Earth system models. Because of the complexity in multiscale modeling, it remains unsure of how to capture the regional process for the global scale modeling. The inaccurate parameterization of the urban processes on a regional scale may even exacerbate the problem. On the other hand, uncertainties also come from the data, such as the global land use/land cover data. In addition to the sparsity of socioeconomic data for the global modeling, the social, environmental, and infrastructural heterogeneity is usually not well represented in the global data, which further hinders the reliable assessment (e.g., environmental justice research). Recent efforts have been put forth to develop high-resolution datasets (e.g., global urban footprint data) and unleash the power of machine learning and remote sensing for data fusion and modeling.

Section 5: Sectors and Systems Breakout

Sectors are a useful frame through which to organize and understand the complexity of urban systems. In the MSD context, sectors are made of infrastructure, social, and environmental systems that function together to provide a service. For instance, the water sector includes the systems of conveyance and treatment infrastructure that move fresh water to and waste water away from users in addition to the source water supplies, water regulatory and management institutions, technologies, and markets that influence the provision and use of water. Sectors act as behavioral aggregators through which many individual decisions combine to yield larger scale impacts. As an example, many individual water (or energy) choices impact regional resources (or the global atmosphere). Sectors also typically correspond with well-established regional regulatory institutions such as water management agencies, departments of public health, public utility commissions or land use authorities, so they are an important place to examine the options for system-wide adaptive responses and longer-term transformational change.

Sectors do not operate in isolation. They are linked with one another through infrastructure system dependencies, environmental connections, and social dependencies. As highlighted in the hazard breakout sessions, some of the most concerning impacts of environmental extremes are failures that cascade through multiple sectors. The water sector is a major user of energy; land use impacts water availability and quality; access to energy is critical for health in the context of extreme heat; and social inequality limits who can access the services within multiple sectors simultaneously, creating compounding risks and limiting both individual and collective adaptive capacity.

In this breakout session, we took a sector-specific lens to examine the most pressing challenges faced by urban communities in maintaining resilience in the face of climate change. For each sector, participants were asked to examine:

- what are the key vulnerabilities faced by people and systems in this sector
- how do sectoral outcomes (e.g., provision of services, affordability, health outcomes) differ across communities and why
- what kinds of decisions or behaviors control the dynamics of the sector, and at what social scale do those decisions and behaviors take place
- what are the key point of interaction across sectors and among human and natural systems within sectors
- in addition to climate change, what other trends influence or create stress for this sector (e.g., decarbonization trends, population growth)
- what options are available to adapt and create more resilience within the sector and what tradeoffs might these measures have (e.g., financial or energy costs, land use constraints, barriers to full adoption, influences on other sectors)
- What are the most pressing science gaps that must be filled to inform the questions above and what are the promising strategies for addressing those gaps including

5a: Energy

The energy sector is facing multifaceted challenges due to climate change, extreme weather events, and increasingly dynamic demands due to on-site renewable energy generation, charging and discharging of electric and thermal energy storage including electric vehicles, as well as variable supply from the power grid due to more intermittent renewable energy generation. Three overarching themes were identified and discussed at the breakout: 1) the challenge of simultaneously decarbonizing and adapting the energy sector to climate change, 2) energy security, and 3) energy burden and equity.

The energy sector aims to fully decarbonize for 100% clean power, a strategy that is underpinned by large-scale electrification of end-uses currently powered by gas and liquid fuels. However, electrifying the energy sector has important implications for the timing of peak demand. For example, widespread adoption of heat pump technology for space and water heating may lead to a winter peak electricity demand comparable to the current summer peak demand. Deep retrofitting of the existing building stock to increase efficiency and reduce energy demand can mitigate demand increases from electrification. Increased reliance on a single source of energy (i.e., electricity) potentially increases societal risk, especially during extreme weather events (e.g., heatwaves, cold snaps) that lead to power outages. Research on large-scale modeling and analysis is needed to provide actionable and localized strategies and solutions to inform stakeholders to plan and execute energy sector decarbonization in tandem with resilience efforts.

With energy supply and demand becoming more dynamic and hard to control, balancing both sides is a growing challenge, especially during extreme weather events. Decentralizing power supply may be one of the solutions, e.g., microgrid technology for a community to operate in an island mode during grid power outage. Storage technology is essential to help balance demand and supply. Demand side management is another promising solution, which means designing and operating buildings and infrastructure to flexibly increase their energy use when the grid has sufficient power and use less at other times.

Communities with a high energy burden (defined as the percentage of household income spent on energy) often face multiple intersecting challenges that increase risks associated with loss of energy access and also prevent full adoption of clean energy technology necessary to support decarbonization. The building stock in such communities is often less energy efficient, contributing to higher energy costs and carbon emissions. Low-interest financing, incentives and rebates, as well as low-cost technologies are needed for all communities to be part of the energy transition.

The energy sector interacts with the buildings, transportation, urban environment, and social-economic systems. In a warmer urban environment, buildings need more cooling, and they emit more heat which can further warm the urban environment leading to more cooling demand forming a closed loop. Modeling related sectors together can capture their interactions and understand cascading effects. Large scale urban energy modeling supported with big data, machine learning and high-performance computing will help researchers and stakeholders identify, evaluate, and prioritize strategies for the energy sector to achieve simultaneous decarbonization and resilience goals.

5b: Water

Challenges to the water sector fall into three broad (but interconnected) categories: climate change, financial, and social. Challenges associated with climate change are further stratified by region. The eastern parts of the United States (including the Gulf Coast) are increasingly confronted with too much water (as a result of more frequent/intense precipitation events). The western parts of the United States are increasingly confronted with decreased availability and access to water, yet still must contend with increased intensity of wet extremes due to earlier spring snowmelt and enhanced magnitude of individual storms. Indeed, finding solutions to manage wet extremes by capturing large volumes of water when they are available may be an important aspect of managing dry extremes. Challenges associated with drought and increased water scarcity are exacerbated by social factors such as laws and institutions related to water allocation and practices related to land use. The established rules and institutions for allocating water were established in a world with very different ecological and social contexts (i.e., a world where water was more available and faced with less competing demands). However, these rules and institutions appear to be misaligned with our current context (i.e., a world with a changing climate, changing demands, and growing scarcity). Similarly, certain land use practices (e.g., green lawns at every household; water-intensive agricultural activity in water-scarce locations) also appear to be misaligned with our current context. Finally, there are financial challenges associated with the water sector. Generally speaking, water is not treated as a scarce good (i.e., its price is often “artificially” low)

Some of the pressing science gaps and associated opportunities for addressing the issues above include collecting more robust groundwater pumping data (to gain a better understanding of the rate at which groundwater is being depleted) and modeling the reliability of nature-based solutions at large scales and under extreme conditions (to gain a better understanding of whether green infrastructure and nature-based solutions can actually be a one-for-one replacement for traditional infrastructure). Some of the biggest gaps and opportunities in the water sector are not purely scientific, but instead relate to our decisions and preferences about how water is used, and how much it should cost. This points to the value in co-producing scientific knowledge with decision-makers to ensure that those decisions are supported by scientific evidence and that the research community produces the evidence that is most needed.

5c: Health

Health is both a primary outcome of interest to society and an enabling condition for individuals to participate fully in the economic and social life of an urban community. Environmental conditions such as air quality, and exposure to heat extremes have direct impacts on health.

Such conditions are often correlated with sociodemographic factors, as well as built environment characteristics across the heterogeneity of urban landscapes. In the context of climate change, these environmental health concerns may be exacerbated, certainly with respect to extreme heat.

The health sector faces a unique data challenge that many other sectors discussed during this workshop do not: data access. This challenge does not imply a lack of data, per se, because there is an abundance of health data. However, due to privacy concerns and other challenges, health data is often aggregated to a level that obscures the differential risks and outcomes across different communities and makes it challenging to intersect that data with environmental and built systems data at the native scale of their variability within urban areas. The representativeness of health data is also a concern. Marginalized individuals who are missed in data collection efforts are often most at risk of numerous negative health outcomes. Citizen science can help to bridge this gap, but such efforts are not systematic across the United States and world more broadly.

Section 6: Epistemology Breakout

The Model-Observation-Experiment (ModEx) cycle (U.S. DOE. 2018) provides a paradigm for understanding how different methodological strategies collectively contribute to advancing knowledge and informing future decisions in Environmental System Science. This cycle highlights the role of observations, experiments, model development, and uncertainty analysis, all in a multiscale context, for continually refining our best understanding of environmental systems.

In this workshop, we agreed that research which aims to understand and address fundamental uncertainties about urban contexts needs to be grounded in human-scale and human-centric perspectives. This shift requires including additional epistemological strategies, both because of the different scale of potential uses, and because of the different levels of existing scientific consensus in environmental system science as compared to the science of cities.

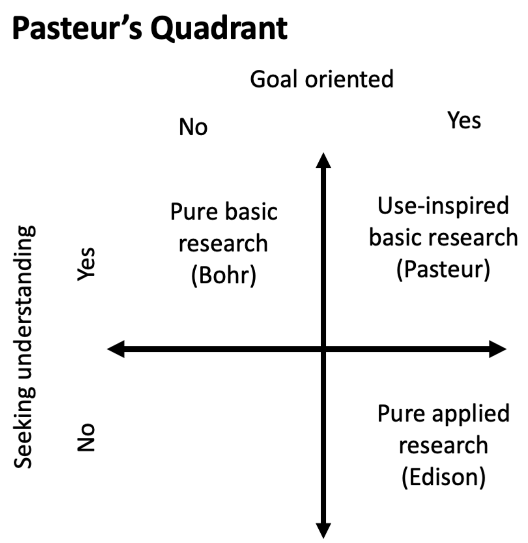

Figure 2: 'Pasteur's Quadrant' model of scientific research objectives, reproduced from Stokes (1997). Science can be motivated primarily around seeking basic understanding of a phenomena, around meeting a goal or objective, or both. The DOE is a mission-oriented organization, and so most DOE-funded research centers around its potential applications and importance. Some of this research is fundamental: seeking a basic understanding of important phenomena. Other aspects are directly applied: seeking to manage, control, or otherwise support the decision-making process.

Figure 2 shows the 'quadrant' model of scientific research objectives (Stokes 1997). The objective of urban scientific research for environmental system science can include both learning how urban environments influence the larger scale Earth system, and the translation of larger scale environmental system findings into human-centric and decision relevant scales. Translating environmental system findings into human-centric and decision relevant scales allows and requires use of epistemological strategies which are not currently included in the ModEx cycle. Communities, cities, and regions are the scale at which climate hazard impacts are felt, they are the scale at which decisions can be made, and there hasn't yet been enough actionable science aiming to characterize the consequences of changing climate and climate hazards at these scales. Urban decision makers and stakeholders have the best available understanding of how those climate risks and hazards impact cities across the range of interacting urban systems, sectors, and socio-economic groups. Using this knowledge to define critical research questions will enable research to fill those scientific gaps at human-centric scales more easily. This is most efficiently done through knowledge co-production by including urban stakeholders in the development of urban research questions and goals.

Another epistemological shift from the ModEx cycle is related to the extraordinarily strong scientific consensus around the most significant parts of the physics and processes which are driving climate change. The latest IPCC report makes the scope and breadth of this consensus very clear (Masson-Delmotte et al. In Press). Research at human and urban scales has nowhere near this level of scientific consensus.

Human-centric research has long been hampered by a lack of sufficient human and behavioral data at a scale large enough to observe generalizable patterns. For example, noted urbanist Jane Jacobs (1992), generated a number of influential hypotheses about the processes which well-functioning urban environments must have. However, her work was entirely qualitative because at that time there was not sufficient data available to test or validate her core hypotheses. Quantitative testing of her hypotheses has taken decades, in part because of these substantial data gaps. Now that the digital trace data explosion is providing large scale observational data on human-scale activities, interactions, and movement patterns, the qualitative hypotheses and theories resulting from decades of careful social science research can be tested, validated, and eventually provide the foundation for empirical models and quantitative theories of urban systems and processes.

From another perspective, Emanual (2020) writes about the risks of a research approach which too-heavily weights simulation and computation in Earth System research. Emanual is concerned that this context risks creating conditions where too little attention is given to process-based understanding and theoretical development, thus hindering our overall scientific progress. In both cases, an epistemological approach is needed which balances observation, theory, modeling, and knowledge co-generation to advance basic understanding.

In four breakout sessions, we explored strengths and weaknesses for epistemological strategies across the different urban hazards, sectors, and social scales, organized around identifying research domains which have:

- sufficient data and synthesis strategies?
- theories which explain most of the observed phenomena?
- models which represent the system sufficiently well?

• an existing ecosystem of collaboration which can communicate decision-maker points of uncertainty and leverage to modelers, and can communicate model content and findings to decision-makers?

6a: Data and Machine-Learning Models

Growing availability of data and progress in data processing technologies create new opportunities for urban research and decision support. However, these advances also elucidate important remaining barriers, such as: imbalance in availability and quality of different datasets that become equally critical for complex questions (e.g., public versus environmental health datasets); constraints on granularity of accessible data (e.g., lack of household-level or utility system data); limited consistency in data collection and quality controls, and similar. Given the broader challenges and high costs of comprehensive and ubiquitous data collection, it may be more practical to strategically focus on "closures" in complex research questions or decision-making and key data required to achieve such closures. Similar considerations arise with respect to urban environmental justice and hazard mitigation, where the decisions based on the data often need to be made quickly. In this regard, it becomes especially critical to understand the pathways by which the data can lead to decisions swiftly and robustly, and strategies to assess the efficacy of expenditures to tune future decision-making.
Machine-learning models are increasingly seen as a powerful strategy both for arriving at complex decisions with the help of massive and heterogeneous datasets, and for predictive forecasting in decision support for future urban scenarios. However, despite their expanding use, machine-learning models are not yet widely regarded as trustworthy due to complex, "black-boxy" operation, potential sensitivity to sampling biases in data, and lack of rigorous parameterization and testing. The robustness of machine-learning models in urban applications can be enhanced by more ubiquitous adherence to best practices such as testing them as a hierarchy of models with increasing complexity that is analytically tractable; examining whether the same phenomena captured by different mixes of data can be robustly implemented by the model, and combining machine-learning algorithms with hybrid or mechanistic models that more robustly account for realistic processes and causal relationships.

6b: Theory and Frameworks

The development and application of quantitative theory about anthropogenic processes substantially lags the development of theories for physics-based earth system processes. This is a major gap that impedes our ability to understand and predict outcomes in Earth system processes that we care about. There are statistical models of aggregate patterns of human behavior, and tools like agent-based modeling are very useful for demonstrating a minimum rule set required to observe aggregate behavioral phenomena. This includes game theoretic results such as the prisoners' dilemma and results on simple models of collective behavior such as Schelling's rule. Any of these can be applied in aggregate, spatially or over a network. These kinds of tools have important applications in transportation modeling, crop choice, and other repeated choices in a stable social and physical context. However, they are less applicable to real-world changes as the physical, social, and ecological context changes because we lack robust techniques for understanding how *collective* behavior may change in response to large changes in context.

Understanding the aggregate signatures of behavior change that occurs in response to dramatic changes in context (for example the COVID-19 pandemic) is critical to thinking through potential behavior patterns under a changed climate. However, these individual responses in changing contexts are heavily dependent on higher order social choices - for example the extent to which threats are communicated to people, and the response strategy used by local and higher order social organizations. Theoretical tools at the community, city and regional scale are more limited, and while important models of global scale processes exist, such as GCAM (Calvin et al. 2019), they are not designed to represent the kinds of widespread behavior changes that do occur during extreme context changes - both short term and permanent. This leads to a particularly significant gap in strategies for identifying statistical regularities in higher order anthropogenic processes, like institutions and governance. Because of this gap on the 'human' side, Urban MSD research needs more investment in integrating theories across disciplines, urban sectors, systems and processes. These integrating theories could provide mechanisms for characterizing when and how systems influence each other, and when those influences are strong enough to matter for a given outcome of interest. Addressing theory and model uncertainty in the context of feedbacks across sectors, systems and scales is also important.

6c: Modeling

Accurate representation of urban areas and urban processes at microscale, regional, and global scales and their feedback across scales, is required for understanding how humans affect and are affected by climate change. Cities are responding to challenges related to migration, urbanization, inequity, and health, in addition to coping with extreme climate events with increasing intensity and frequency. To address these challenges, cities must strategically increase their adaptive capacity, and urban-resolving climate models are needed to facilitate that adaptation and understand the role that cities play in local, regional, and global climate change (Sharma, Wuebbles, and Kotamarthi 2021). Agencies such as the World Meteorological Organization have recognized that these challenges necessitate new types of data, modeling, and services such as dense observation networks, high-resolution forecasts, and multi-hazard warning systems to build resilient and sustainable cities (Baklanov et al. 2018). To relate these observations and forecasts at city scale to their overall effect on global climate, processes that are strongly non-linear and influenced greatly by urban phenomena must be identified and represented in global models in ways that preserve this non-linearity within their urban subgrid parameterizations (Sharma, Wuebbles, and Kotamarthi 2021).

Ortman, Lobo, and Smith (2020) describe urban areas as "networks of social interaction embedded in physical space." Yet understanding the communication of these networks with the physical space is partly where our modeling challenge lies. How economic activity, population dynamics and growth, transportation, water treatment, energy, and other critical infrastructure drive and shape the physical space of an urban area still lacks cohesive theory. Furthermore, social, natura,l and structural aspects of urban areas are unique to each area and difficult to generalize. Also, because characteristics of urban built forms play roles in weather and climate models as atmospheric boundary conditions and airflow pathways, and structures such as urban water distribution systems can contribute greatly to localized urban floods, but neither of these components are fully integrated into numerical weather simulations, modeling at the urban scale must still be considered a nascent area of research. Even with the large manual and computation expense of representing these aspects uniquely to each city, mismatches among these urban assets can lead to difficulties in validating models and to ultimate model failure.

Thus, integrated modeling at the urban scale is well poised for new research. If we can better understand and represent fundamental atmospheric, environmental and human processes as interacting systems, we increase our capacity to explore different urban land use trajectories or future climate scenarios and conditions and to integrate processes occurring at neighborhood scale more reasonably with those at regional and global scale.

6d: Knowledge Co-Production

In urban sustainability research, it is widely recognized that knowledge co-production is an extremely valuable strategy for ensuring that research investments produce knowledge that addresses the problems they aim to solve (McPhearson, Iwaniec, and Bai 2016; Markolf et al. 2018; Hino and Nance 2021). Knowledge produced in collaboration with relevant stakeholders is more tuned to the actual problems at hand and is consistent with the use-inspired science that is central to the DOE mission. This knowledge is both designed around stakeholder needs and concerns and is more readily accepted into practice both because it is more relevant and also because there are already trusted emissaries between researchers, stakeholders, and the broader community.

However, a number of structural impediments in the research system make genuine collaboration difficult. Centrally, academic investments typically have a very short investment period relative to the timeline of the social processes that build trusting working relationships, most especially when stakeholders are volunteering their time, while the researchers are paid. When researcher-stakeholder relationships cross cultural, racial, and socio-economic lines, miscommunication is more likely, trust takes longer to build, and is easier to lose. People whose personal experience and history allows them to span those boundaries are particularly critical for ensuring success in knowledge co-production. Stakeholder burnout occurs when engagement patterns don't meet their needs. However, these relationships must exist for knowledge co-production to become possible.

Successful examples of urban researcher-stakeholder collaborations exist, for example through the Decision Center for a Desert City (DCDC), the Urban Resilience to Extremes Sustainability Research Network (UREx SRN), the SETS Convergence Network, and the Baltimore Ecosystem Study Long-Term Ecological Research. The Decision Center for a Desert City is centered around urban water systems. UREx SRN and the SETS Convergence Network focus on integrating social, ecological, and technical systems to devise, analyze, and support urban infrastructure decisions in the face of climatic uncertainty. The Baltimore Ecosystem Study investigates the ecological, cultural, and economic forces that shape the Baltimore area.

Research that aims to advance equity and environmental justice goals in urban contexts must develop strategies to address these structural impediments to knowledge co-generation, so that the research community can benefit from local knowledge, understanding, perspectives on issues of critical local concern, and potential community-based solutions.

Section 7: Concluding Perspectives

7a: Environmental Science

Urban areas are embedded within and co-evolve with larger environmental systems such as the atmosphere, ecosystems, and the hydrosphere. For any given field of environmental science, we can ask two broad questions - how do the unique properties of urban areas alter key environmental processes, and how do environmental processes in turn influence the evolution of urban systems? For example, consider the field of hydrology. Impervious surfaces exist outside of cities, but their high prevalence in urban areas alters groundwater recharge and surface runoff processes in important ways. There are also entirely new processes in urban areas that must be considered to understand hydrologic phenomena, such as the existence of drainage infrastructure, and prevalence of highly managed and irrigated vegetation. On the other hand, hydrologic processes shape flood dynamics and water availability in ways that constrain or enable choices regarding what can be built and where, or what is a desirable and safe place to live, work, and recreate. Environmental shocks can propagate through highly coupled urban sectoral systems, such as when flooding leads to failure of energy or transportation infrastructure. Likewise, uncertainty regarding future environmental conditions can propagate through multiple systems to create uncertainty with respect to key outcomes such as resource availability, infrastructure reliability, and health.

The heterogeneity of urban areas poses several challenges for observing and modeling environmental processes, as does the presence of unique and highly coupled processes not found outside urban areas. Dense observations at the native scale of variability are valuable for ground-truthing more coarse observational products, and the integration of multiple types of observation are often required to disentangle interacting processes and phenomena. From a modeling standpoint, it is important to investigate what degree of heterogeneity must be represented to adequately understand and predict key outcomes of interest. Attention to fine-scale heterogeneity is particularly important for assessing factors related to environmental justice, where local-scale heterogeneity in exposure to environmental risks and hazards is regularly concentrated in socio-economic populations that are already most vulnerable along other dimensions. Adequately characterizing highly variable human-influenced boundary conditions (either observed or in the context of hypothetical future scenarios) can be a limiting factor for models. Representing the unique processes that arise through interaction with built and social systems within environmental system models can take place through the development and testing of new model codes or through coupling with existing models and data from infrastructure system science and social science.

7b: Infrastructure System Science

Infrastructure systems are the most significant mechanism through which cities influence the broader Earth system. The scale of human activity that our infrastructure systems enable creates the capability for very large scale carbon emissions. Transportation systems enable the movement of materials and resources from hinterlands into cities. Energy systems enable the movement of energy across long distances and into cities, providing the energy needed to sustain cities, while engineered water systems move water within and across hydrologic basins, meeting basic human water and sanitation needs. Telecommunication systems transmit information globally and enable ideas generated in cities to be used anywhere.

Physical infrastructure systems are also a major mechanism through which the adverse effect of climate change will be experienced. They are designed to be long-lasting and extremely robust to a wide range of environmental and anthropogenic disturbances. However, these infrastructure systems typically cannot adapt to conditions outside their design parameters. This makes them vulnerable to failure when the environmental and human activity context changes. Because urban infrastructure systems are so closely coupled, infrastructure failures in one sector or location can have cascading and sometimes catastrophic consequences. This points to a need for scientific insight into the vulnerability of existing built infrastructure systems and their coupled behavior, as well as insight into the performance of hypothetical future infrastructure systems and how they might perform in the context of future environmental and social conditions.

The increasing availability of real-time observations that include environmental conditions, infrastructure status, and behavioral responses is of great value for managing infrastructure systems flexibly within the context of ongoing environmental extremes, and can also be leveraged to gain fundamental insight into the coupled behavior of these systems across a range of conditions. However, many anticipated extreme events of the future are out of sample in the historical record. This is due in part to the definition of extreme events as rare and therefore not frequently observed, and in part to the non-stationary distribution of possible events due to changes in the climate, socio-economic processes, and technology. Complementing data rich methods such as machine learning with physics-based and process-rich models is a promising avenue for exploring a range of plausible hypothetical futures and gaining insight into the multi-objective outcomes associated with alternative infrastructure development pathways.

7c: Social Science

By a substantial margin, the biggest sources of uncertainty in Earth system outcomes are due to anthropogenic processes. The largest uncertainty in the global future climate is anthropogenic carbon emissions: as in Figure 3 below, uncertainty across climate scenarios is far larger than uncertainty within any given scenario. This feature is repeated across geographic scales and environmental contexts: the biggest sources of uncertainty in urban water cycles are human decisions about land use and land cover change; for coastal wetland loss it is “will humans protect wetlands, or not?”; and for algal blooms it is the decisions farmers make about fertilizer use. Lack of attention to the anthropogenic processes driving these outcomes impedes our ability to understand the coupled and co-evolving aspects of the human-Earth system, as well as our ability to reduce overall scientific uncertainty in the future climate.

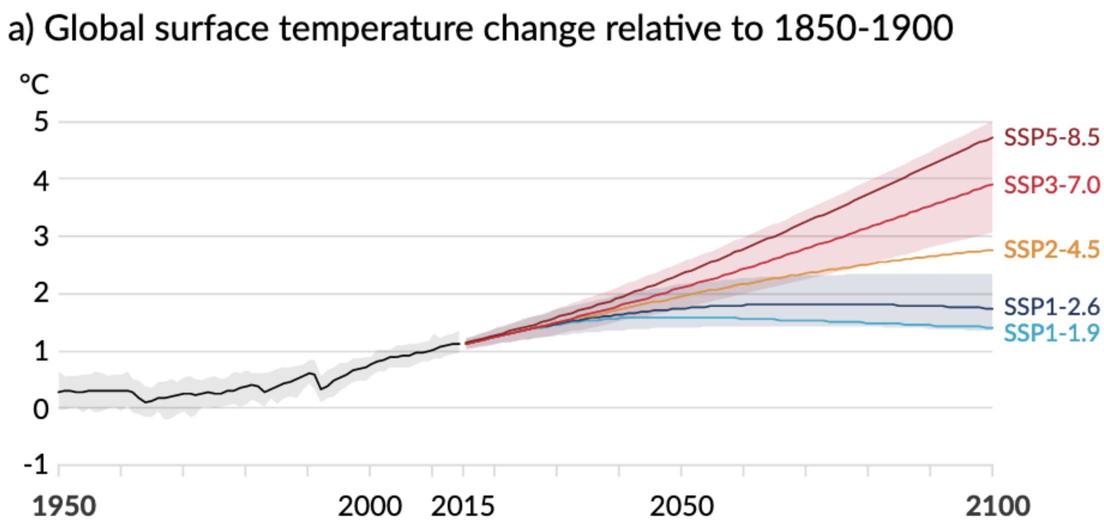

Figure 3. Reproduced from IPCC 6th Assessment Report, Summary for Policy Makers, Figure SPM.8a.(Masson-Delmotte et al. In Press)

Some of the most significant outstanding climate research questions are about its impacts: when, where, and by how much can we expect climate hazards and climate change to impact human activities, and the extent to which these hazards differentially impact marginalized and vulnerable communities. A critical aspect of understanding expected climate impacts is understanding how individuals and organizations might respond to climate hazards and the anticipation of those hazards. These responses depend heavily on the level of heterogeneity in access, resources, and exposure that different groups within a city experience. Cities and regions are a primary scale at which climate impacts are felt and at which decisions can be made. Yet, there hasn't yet been enough actionable science aiming to understand the consequences of changing climate and climate hazards at these scales.

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Appendices:

Appendix A: Workshop Agenda

Wednesday July 21

10:00 - 10:20 (Pacific)	**Welcome and Workshop Overview**
	Christa Brelsford and Andrew Jones
10:20 - 10:30	**MultiSector Dynamics Community of Practice Overview**
	Richard Moss
10:30 - 11:30	**Keynote Speaker Panel**
10:30 - 10:45	Multi-Sector System Science for a Net-Zero Emissions Future
	Anu Ramaswami
10:45 - 11:00	Science ingredients and research gaps in urban resilience and community sustainable development
	Luis Bettencourt
11:00 - 11:15	Urbanization as Global Change: Key Trends and Knowledge Gaps
	Karen Seto
11:15 - 11:30	Advancing Research in Modeling Coupled Urban Systems and Making it Useful in Decision Support
	Paul Waddell
11:30 - 11:55	Moderated Discussion
11:55 - 12:00	Concluding Thoughts and Workshop Overview

Thursday July 22

8:00 - 9:30 (Pacific)	**Breakout Session 1 - Climate Hazards**
8:00 - 8:10	Intro: *Andy Jones*
8:10 - 9:10	Breakouts
	Extreme Heat
	Flooding
	Drought
	Wildfire and Smoke
9:10 - 9:30	**Groups Share Highlights**
9:30 - 10:00	Break, Zoom will remain open
10:00 - 11:30 (Pacific)	**Breakout Session 2 - Social Scales**
10:00 - 10:10	Intro: *Christa Brelsford*
10:10 - 11:10	Breakouts
	Individual and Household
	Community and Neighborhood

		City and Regional
		National and Global
11:10 - 11:30	Groups Share Highlights	
11:30 - 12:00	Break, Zoom will remain open	
12:00 - 1:30	**Networking Session**	
12:00 - 12:45	'Speed dating' in groups of 2-3	
12:45 - 1:30	Breakout rooms available for additional conversation	

Friday July 23

8:00 - 9:30 (Pacific)	**Breakout Session 3 - Sectors and Systems**	
8:00 - 8:10	Intro: *Andy Jones*	
8:10 - 9:10	Breakouts	
		Energy
		Water
		Built Environment
		Health
9:10 - 9:30	**Groups Share Highlights**	
9:30 - 10:00	Break, Zoom will remain open	
10:00 - 11:30 (Pacific)	**Breakout Session 4 - Epistemologies**	
10:00 - 10:10	Intro: *Christa Brelsford*	
10:10 - 11:10	Breakouts	
		Observations, Data Science, and Machine Learning
		Theory and Frameworks
		Modeling
		Decision Science and Co-Production
11:10 - 11:30	**Groups Share Highlights**	
11:30 - 12:30	Break, Zoom will remain open	
12:30 - 1:30 (Pacific)	**Synthesis Session**	
12:30 - 1:00	Rapporteur Key Take-Aways	
1:00 - 1:30	Open Plenary Discussion	

Appendix B: Speaker Biographies

Dr. Anu Ramaswami is a pioneer in the topic of sustainable urban infrastructure systems. Her work explores how cities' physical systems shape environmental sustainability, human health and wellbeing, and distributional equity from local to global scales.

Dr. Luis Bettencourt is the inaugural director of the Mansueto Institute for Urban Innovation. His research investigates the fundamental processes that drive, shape and sustain cities - and the opportunities that come with being a city in the 21st century.

Dr. Karen Seto is one of the world's leading experts on contemporary urbanization and global environmental change. She is leading the urban mitigation chapter for the IPCC 6th assessment report.

Dr. Paul Waddell leads the development of the UrbanSim model of urban development. His research focuses on assessing the impacts of planning choices on outcomes such as spatial patterns of real estate prices, travel behavior, and emissions.

Appendix C: Participant Biographies

Melissa Allen-Dumas (she/her)

Melissa Allen-Dumas is a Research Scientist in the Computational Sciences and Engineering Division of Oak Ridge National Laboratory. She holds a Ph.D. degree in Energy Science and Engineering and a MS degree in Environmental Engineering from the University of Tennessee. Her expertise includes global modeling and analysis of atmospheric species transport, statistical and dynamical downscaling of various climate model output, analysis of direct and indirect effects of climate change on electricity demand, and on other national and civic critical infrastructures. She is the lead for the ORNL Impacts, Adaptation, and Vulnerability theme within the Climate Change Science Institute; and a member of the Urban Dynamics Institute.

Reginald Archer (he/his)

Reginald Archer applies Geographic Information Systems/Science & Remote Sensing and the “science of where” to analyze spatial data and conduct research, specifically environmental change related to precision agriculture, sustainability, public health, hazards, vulnerability, disaster recovery and environmental justice. He teaches multiple courses related to Geospatial applications at both undergraduate and graduate level, and incorporates culturally relevant content and experiential learning to further engage his students.

Jeff Arnold (he)

Jeff Arnold is a Senior Scientist and the Lead Climate Scientist with U.S. Army Engineers, where he works on the technical and science-policy concerns of climate change for water and energy security. He's also the national manager for the Army Engineer Responses to Climate Change Program that collaboratively creates and uses computational hydro-climatology for characterizing climate change threats and for testing possible adaptation responses for water and energy security.

Christa Brelsford (she/her)

Christa Brelsford is a Research Scientist in the Geospatial Science and Human Security Division at Oak Ridge National Laboratory. Her research uses data science tools from economics, geography, network science and spatial statistics to describe the co-evolutionary processes between human systems and the built and natural environment. These analyses have been particularly focused on urban contexts; exploring themes of urban water management, infrastructure provisioning and resilience, and human behavioral responses to surprising events.

Melissa Bukovsky (she/her)

Melissa Bukovsky is a Project Scientist III at NCAR. Her research focuses on climate change in North America, and spans regional climate modeling, climate analysis, and climate change impacts. Some of her current areas of work include the examination of the influence of climate change on extratropical cyclones, fire, and the influence of potential future land-use scenarios on climate change projections.

TC Chakraborty

TC's broad research interests are in understanding how the exchange of moisture and energy between the land surface and the atmosphere influences local weather and climate; and in particular, the influence of highly heterogeneous terrain, like cities, on boundary layer dynamics.

Siling Chen

Siling Chen has a M.Sc. degree in Water Resources and Environmental Management and a B.Sc. degree in Environmental Sciences. For her current research as a Ph.D. candidate at Technical University of Berlin, she is especially interested in the dynamics within urban water systems and their interconnection with other urban critical infrastructures (e.g., urban planning, electricity, IT, mobility).

Ronald C Cohen (he/him)

Ronald C. Cohen, Ph.D. is Professor of Atmospheric Chemistry at the University of California, Berkeley. He was Director of the Berkeley Atmospheric Science Center from 2006-2016. Cohen is known for his work on the atmospheric nitrogen cycle, the temperature dependence of ozone and urban emissions of greenhouse gases. He is a fellow of the American Association for the Advancement of Science and the American Geophysical Union. Cohen has mentored over 50 Ph.D. students and postdoctoral fellows and is co-author of over 280 peer-reviewed scientific papers.

Bill Collins

Dr. William Collins is an internationally recognized expert in climate modeling and climate change science. He is the Director of the Climate and Ecosystem Sciences Division (CESD) for the Earth and Environmental Sciences Area (EESA) at the Lawrence Berkeley National Laboratory (LBNL), a Professor in Residence in the Department of Earth and Planetary Science at the University of California and the director of the Carbon Negative Initiative at LBNL

Iryna Dronova (she/her)

Iryna Dronova is an Associate Professor jointly appointed in the Departments of Landscape Architecture & Environmental Planning (College of Environmental Design) and Environmental Science, Policy & Management (College of Natural Resources) at the University of California, Berkeley. Her research combines landscape ecology with geographic information science and remote sensing to investigate multi-scale dynamics of human-dominated landscapes and enhance their cost-effective monitoring. Her recent research focuses on urban warming in different climatic and socio-economic contexts and strategies to mitigate the controversial socio-economic benefits of urban green space while increasing its cooling potential together with accessibility and other multifaceted benefits.

Katherine Evans (Kate/she)

Katherine J. Evans is the Division Director for the Computational Sciences and Engineering Division at Oak Ridge National Laboratory (ORNL). She serves on the leadership team for

ORNL's Climate Change Science Institute, the leadership council for the UT Chattanooga SimCenter, and as a representative for the DOE's Biological and Environmental Research program on the coordination committee of the DOE Scientific Discovery through Advanced Computing (SciDAC) program. Evans is also an active researcher in the areas of Earth system model (ESM) evaluation, developing and implementing scalable numerical algorithms to improve the efficiency and accuracy for multi-scale configurations of ESM, and analysis of large-scale persistent weather patterns in global atmospheric models. As part of her numerical methods research with ESM, she also makes connections to other applications, including more general fluid flow, energy impacts, disease propagation, and oncology.

Chao Fan

Chao is a postdoctoral research associate in UrbanResilience.AI Lab in Zachry Department of Civil and Environmental Engineering at Texas A&M University. He received his Ph.D. in Civil Engineering at Texas A&M University in December 2020, M.S. at the University of California Davis in June 2017, and B.Eng. at China University of Mining and Technology in June 2016. His research focuses on urban intelligence and smart resilience, a quest to develop transformative solutions to global sustainability challenges of urban infrastructure systems in ever-changing conditions, using data and human-machine intelligence.

Gerald Geernaert

Gerald (Gary) Geernaert has been Director of the Earth and Environmental System Sciences Division at DOE since 2010. In appointments, he was the Director of the Institute of Geophysics and Planetary Physics at Los Alamos National Laboratory, director of the Atmospheric Environment Department at the Danish Environmental Institute, and Program Manager at the US Office of Naval Research. With research and adjunct faculty appointments, he has taught science policy and has produced over 100 archivable publications including four books.

Tianzhen Hong (he/him)

Dr. Tianzhen Hong is Senior Scientist of Building Technologies Department of LBNL. His research employs interdisciplinary approaches with data, analytics, modeling, and simulation to explore technologies and human factors supporting the planning, design and operation of energy efficient, demand flexible, and climate resilient buildings at multi-scale. He is an IBPSA Fellow and ASHRAE Fellow.

Susan Hubbard (she/her)

The Earth and Environmental Sciences Area (EESA) that I lead at Berkeley Lab focuses on research to simultaneously enable sustainable environmental stewardship and judicious use of the Earth's resources. EESA has defined resilient systems as one of five grand challenges that drive research in the organization, with a focus on urban systems. My personal research focuses on quantifying how complex environmental systems function, with an emphasis on the development of geophysical approaches to remotely sense hydrological, geochemical, biological and geomechanical processes; how these processes couple over scales; and how the integrated processes govern water availability, water quality, carbon cycling, agriculture and subsurface geological system behaviors.

David Iwaniec (he/him)
David M. Iwaniec is a sustainability scientist researching anticipatory and systems approaches to advance urban sustainability and transformative resilience.

Andy Jones (he/him)
Andy Jones is an Earth scientist who works at the interface of human and environmental systems. His research uses quantitative models and data analysis to understand climate change and human-Earth system interactions at decision-relevant scales. He also collaborates with social scientists and interacts closely with stakeholders to understand how science can effectively provide actionable insight into strategies for increasing resilience of energy, water, food, and urban systems. He is a research scientist at Lawrence Berkeley National Laboratory where he leads the Earth Systems and Society Program Domain and the Resilient Systems Grand Challenge theme for the Earth and Environmental Sciences Strategic Vision. He previously served as the Deputy Director of the Climate Readiness Institute. He is also an Adjunct Professor in the Energy and Resources Group at UC Berkeley.

Kuldeep Kurte (he/his/him)
Kuldeep Kurte is currently a research scientist in the Computational Urban Sciences Group (CUSG) at Oak Ridge National Laboratory. He finished his Ph.D. in Image Information Mining from Indian Institute of Technology Bombay, India, in 2017. He joined Oak Ridge National Laboratory as a postdoctoral researcher in scalable geo-computation in January 2018. In his first project at the lab, he worked on developing a scalable end-to-end settlement detection workflow and its deployment on Titan supercomputer. As a part of Urban Exascale Computing Project (UrbanECP) he worked on building a capability to facilitate running several instances of the Transims simulations on Titan. He also worked on the tasks of analyzing a regional scale impact of the inclement weather on traffic speed and coupling Transim's output with the building energy simulation through an efficient spatial indexing approach. Continuing his interest in data-driven urban computing he is currently working on intelligent HVAC control using reinforcement learning for building energy optimization.

Dan Li (he/his/him)
Dan Li is currently an assistant professor at Boston University. He did his Ph.D. and postdoc at Princeton University. He works on a range of topics centered on urban climate and he's particularly interested in the dynamics and thermodynamics of urban atmospheres.

Linqing Luo
Linqing Luo is working on distributed fiber optic sensor development and its application in structural health monitoring, geophysics and environmental monitoring. She received the B.Eng. degree in electrical engineering from the University of Liverpool in 2012 and the M.Res. and Ph.D. degrees from the University of Cambridge in 2013 and 2017, respectively. She's currently with Lawrence Berkeley National Laboratory.

Zachary Malone (he/him)
Zachary Malone is a second year Ph.D. in Environmental Systems at UC Merced advised by Dr. Asmeret Asefaw Berhe and Dr. Rebecca Ryals. He's interested in improving soil health by using organic matter amendments, such as compost and biosolids. He also attended UCM for his undergrad and grew up in the Sacramento area.

Jiafu Mao
Jiafu Mao is a senior research scientist at ORNL. He has a broad interest in different areas of human-land climate interactions. He has been investigating the hydrology, carbon cycling, and vegetation dynamics in the terrestrial ecosystems using field measurements, satellite images, process-oriented land surface and Earth system models, and various statistic methods; he has been quantifying the land feedbacks to the Earth system using the integrated Earth system modeling and detection and attribution frameworks; also, he has been exploring and modeling the responses and mitigation effects of urban vegetation to urban climates.

Sam Markolf (he/him/his)
Dr. Samuel Markolf is an Assistant Professor within the Department of Civil and Environmental Engineering at the University of California-Merced, where his research broadly focuses on applying systems-thinking to sustainability and resilience challenges facing cities and infrastructure systems. Current projects include examining impacts and responses to various disruption scenarios for inter-city transportation systems, as well as analyzing the extent to which interconnected social-ecological-technological systems (SETS) can enhance (or hinder) urban/infrastructure resilience to extreme events. Prior to joining UC Merced, Sam was a Research Fellow for the NSF sponsored Urban Resilience to Extremes Sustainability Research Network (UREx SRN).

Ryan McManamay (he/him/his)
Dr. Ryan McManamay is an Assistant Professor within the Department of Environmental Sciences at Baylor University. Previously, he was a research scientist at Oak Ridge National Laboratory (ORNL) for 6 years, the lead of the Energy-Water Nexus theme within the Urban Dynamics Institute at ORNL, and a Joint Faculty member of the Bredesen Center at the University of Tennessee-Knoxville. Ryan is a spatial ecologist that studies human-environmental systems in order to balance ecosystem and societal needs. Ryan studies large-scale current and future impacts of humans, particularly urbanization and energy development, on river and land ecosystems, and explores strategies aimed to synergize sustainability and resilience endpoints.

Richard Moss
Richard Moss has been at PNNL since 1993. Moss' research includes widely cited publications on climate change scenarios, characterization and communication of uncertainty, and resilience assessment and planning. He served as Director of the US Global Change Research Program, Head of technical support in the Intergovernmental Panel on Climate Change, and in senior leadership positions at the World Wildlife Fund and UN Foundation. He has served on numerous advisory boards and committees (including nearly 15 consecutive years as chair or

member of National Research Council boards). He holds visiting/adjunct affiliations with Princeton University and the University of Maryland.

Greg Mount

Greg Mount is the water resources manager for the EPGMD department of Broward County. He oversees future conditions modeling and adaptation planning. Currently working on RFP solicitations for county-wide resilience plan.

Michelle Newcomer (she/her)

Dr. Michelle Newcomer is a Research Scientist in the Climate & Ecosystem Sciences Division at Lawrence Berkeley National Laboratory. Dr. Newcomer's research focuses on topics in hydrology, groundwater, climate, biogeochemistry, and her research is leading the way in emerging interdisciplinary topics such as how climate impacts surface-water groundwater interactions, biogeochemical cycling, and algal blooms. In her most recent work, Michelle is leading a large-scale long-term watershed approach to understanding watershed changes after fires in a west coast US watershed impacted by multiple and compounding fires each year. Michelle is also leading the river corridor component of the Watershed Function Scientific Focus Area, a large DOE project at the scientific frontier of understanding how watersheds function to deliver water and nutrients downstream.

Peter Nico (he/his/him)

Peter Nico is a soil chemist/geochemist by training and lead the Resilience Energy, Water, and Infrastructure Program Domain in the Energy Geosciences Division of Berkeley Lab. He lead and am interested in different areas of work that are relevant to urban resilience including groundwater management and quality, geothermal direct use and energy storage, urban bioavailability of toxic metals (e.g., Arsenic in play equipment lumber or Chromium in urban aerosols). He likes to think of these topics in terms of their feedbacks with expected changes in urban climates.

Yael Nidam (she/her)

David Padgett (he/him/his)

David A. Padgett is an Associate Professor of Geography, and Director of the Geographic Information Sciences (GISc) Laboratory at Tennessee State University (TSU) in Nashville, Tennessee. In September 2019, Padgett was named an Ethical GEO Fellow by the American Geographical Society in support of his project "Democratizing Geospatial Technology: A Model for Providing Technical Assistance in Community Based Participatory Mapping to Environmental Justice Stakeholder Communities." Padgett, 56, is a native of Baltimore, Maryland and is a graduate of Western Kentucky University and the University of Florida at Gainesville.

Bhartendu Pandey (he/him/his)

Bhartendu Pandey is a Postdoc in the Department of Civil and Environmental Engineering at Princeton University. His research examines urban areas using multiple lenses (including land use, infrastructure, economic activity, and human mobility) to understand their equity and sustainability implications. He uses big data (satellite remote sensing, GIS, national surveys, and social media)—complemented with ground knowledge and fieldwork—to ask and answer compelling questions facing urban science. Specifically, he is interested in the inequality, human health, and sustainability implications of urban infrastructure.

Dasun Perera
Dr. Dasun Perera is Postdoc at the Urban System Group, Lawrence Berkeley National Lab. His current work is related with modeling and optimization of urban energy systems in order to improve the sustainability and climate resilience of cities. Prior to joining LBNL, Dasun was a member of Urban Energy Systems Lab Empa/ETH Switzerland. Dr. Perera completed his Ph.D. in 2019 at the EPFL Switzerland. He is the recipient of several awards including the President's Award for Scientific Publications awarded by President of Sri Lanka, Outstanding Paper in Applied Energy Conference 2017 etc.

Natalie Popovich (she/her)
Dr. Natalie Popovich is a Project Scientist in the Energy Analysis and Environmental Impacts (EAEI) Division at Berkeley Lab and a Justice40 Fellow for the Department of Energy Office of Economic Impact and Diversity. She is an environmental economist whose research focuses on the interactions of land use, networks, and travel behavior. She examines how transportation systems affect community resilience and accessibility. As a Schmidt MacArthur Fellow, she investigated how elements of the circular economy concept could be applied to information flows to improve natural resource management. She is the Board President for Our Climate, a nonprofit advocating science-based climate solutions to support a just transition to a clean energy economy. She completed her Ph.D. in Agricultural and Resource Economics and her MS in Transportation Policy at UC Davis.

Deeksha Rastogi
Deeksha Rastogi is a Research Scientist in Computational Science and Engineering Division at Oak Ridge National Laboratory. She has over 10 years of experience working in the fields of atmospheric and climate sciences. Her research focuses on understanding weather/climate extremes, urban air quality, hydro climate and human systems such as critical infrastructure, urban and energy systems responses to changes in environment at varying spatiotemporal scales. She utilizes a range of earth system modeling tools and scientific data analysis to achieve these objectives. She has authored/coauthored a total of 16 peer reviewed publications, 2 peer reviewed technical reports and 1 encyclopedia book chapter.

Sean Reid (he/him/his)
Sean Reid is a third-year graduate student at UCSB. His research interests are broadly in urban and population dynamics and how they are influenced by climate change, natural disasters, health hazards, and conflict.

Joel Rowland
Scientific background: Landsurface dynamics and hydrology, Lead PI on InteRFACE, Lead on

NGEE Arctic, LANL Deputy PM for EESSD

Becca Ryals (she/her)
Becca is an Assistant Professor of Agroecology at the University of California, Merced. Her research program focuses on ecosystem-based climate solutions, particularly in agricultural and sanitation contexts. Her work investigates controls on and quantification of carbon storage and greenhouse gas emissions, as well as the impacts of management practices on climate change mitigation. A major research theme is the capture, transformation, and beneficial reuse of organic wastes as resources to rebuild soil carbon and contribute to a more productive and just food system.

Nagendra Singh
Nagendra's primary research interests include using remote sensing & spatio-temporal analytics for understanding critical infrastructure risk, population distribution and dynamics, and causes and impacts of land use land cover change. In addition, he is also involved in research involving bioenergy sustainability and climate change impacts.

Gayathri Sivakumar
I wish to pursue my career focused on sustainable technology and energy conservation in the forthcoming years. I thought this meeting would be a good start. I have my Master's in Instrument Technology and PhD from Instrumentation and Applied Physics from Indian Institute of Science, Bangalore.

Kevin Sparks
Kevin has been at Oak Ridge National Laboratory since August 2015. He works on solutions to better understand population dynamics, using big social media data and large-scale data processing tools. Research projects include understanding the structure and origin of temporal patterns in cities. Prior to joining the Human Dynamics Section, Kevin was a graduate research assistant at Penn State where he worked on crowdsourcing techniques and machine learning techniques to improve land cover datasets.

Josh Sperling
Josh Sperling is an 'Urban Futures and Energy-X Nexus' engineer, project leader and multi-disciplinary researcher at the National Renewable Energy Lab. His work focuses on why decisions to design environments are rapidly evolving, and how to help underserved and urban communities to be healthier and more sustainable through interdisciplinary, human-centered, and integrated system approaches. Josh co-leads 'smart cities and communities' work across scales, strategic partnership development globally, and supports various urban, behavioral, decision science and early career mentoring efforts at NREL and beyond. Dr. Sperling is also a former Fulbright Scholar, and holds a Ph.D. from the interdisciplinary Sustainable Urban Infrastructure program at UC-Denver.

Mark Stacey (he/him)
Mark Stacey's work focuses on the interplay between climate/environmental change and

human activities, mediated by the built environment and infrastructure systems. He has emphasized coastal communities, primarily considering flooding, but with interest in heat, air quality, and other health-related factors.

Jillian Sturtevant (she/her)
Jillian Sturtevant is a second-year environmental science Ph.D. student. She's interested in city planning and how it can evolve to better consider conservation of the natural environment to preserve biodiversity. Most of her work is done with GIS and R programming to develop geospatial models. Her most recent project uses Clark County, Nevada as an area of study. Our objective is to create a predictive model through a random forest machine learning algorithm to determine building height and footprint from a series of predictive variables such as base elevation, land use/cover, population, etc.

Joe Tuccillo (he/him/his)
Joe Tuccillo is an Associate Research Scientist in Human Geography in the Geospatial Sciences and Human Security Division at Oak Ridge National Laboratory. His research, centered in computational social science and spatial demography, seeks to enhance high-resolution population and occupancy estimates with detailed demographic profiles that contribute knowledge of the linkages between people and the communities in which they reside and interact. Joe is the project lead for UrbanPop, a spatial microsimulation framework that produces high-resolution daytime and nighttime synthetic populations to aid planning and decision support objectives in areas including environmental hazards, public health, and energy/mobility.

Nathan Urban
Nathan Urban works in climate uncertainty quantification, impacts, and adaptation with applications to decision making under uncertainty.

Pouya Vahmani
Working on urban microclimate modeling, climate change and adaptation, regional climate modeling, anthropogenic heating, and heat mitigation.

Robert (Bob) Vallario
Robert (Bob) Vallario is the Program Manager for Multisector Dynamics, Earth and Environmental Systems Modeling, within the U.S. Department of Energy's Office of Science. In his role, he oversees and coordinates a broad portfolio of basic research exploring the complex dynamics among human systems, sectors, and the environment, for example, among water, energy, and land systems/sectors and in environments that range from urban to rural and coastal to inland. Such work considers a range of influences, stressors, and feedbacks spanning weather and its extremes (e.g., droughts, floods, heat waves), changing demographics and population, natural disturbances, land use changes, economic transitions, depletion and discovery of resources, and the role of new, transformational technologies. With a 30-year history at DOE, Mr. Vallario has been an active leader on various crosscutting agency and interagency activities and committees. Prior to joining DOE, he held senior positions at Science

Applications International Corporation (SAIC) and at DOE's Pacific Northwest National Laboratory (PNNL).

Sandra Velarde (she/her)

Sandra is senior analyst at the NZ Climate Change Commission with a focus on forests and climate change mitigation and adaptation. She contributes to policy direction on agriculture and forests, and cross-sectoral issues such as behaviour change and the bioeconomy. Her research background includes: adaptive governance & forest ecosystem services, natural and urban, how cultural values can be incorporated in decision making & public policy, and bioenergy systems innovation. Sandra holds a PhD in Environment from the Australian National University, MSc Ecological Economics (U. Edinburgh) and Forest Engineer and BSc Forest Sciences (Universidad Nacional Agraria La Molina, Peru).

Trivik Verma (he/him)

Trivik Verma is an Assistant Professor at the faculty of Technology, Policy and Management in Delft University of Technology. He leads the Centre for Urban Science & Policy at the department of Multi-Actor Systems. Trivik research focuses on tackling challenges of urbanization in an equitable and just manner. He's particularly interested in understanding the processes that drive and shape urbanization and inequalities from a computational perspective. He focuses on using methods in spatial data science, complex network analyses and participatory mapping to develop computational tools for advancing the theories and practices of urban science.

Yuxin Wu

Dr. Yuxin Wu is a Staff Scientist and the Geophysics Department Head in the Earth & Environmental Sciences Area at LBL. His research focuses on the development and application of novel sensing and characterization methods to infrastructure, energy, and environment topics. His current research topics include (1) Distributed infrastructure sensing; (2) Coupled hydro-biogeochemical dynamics in natural and engineered ecosystems; (3) Joint application of geophysical methods for the characterization and monitoring of the THMC (Thermo-Hydro-Mechanical-Chemical) processes for energy production and waste storage; and (4) the development of novel imaging and sensing approaches for energy and environmental applications.

Zhonghua Zheng (he/him)

Dr. Zhonghua Zheng will join Climate & Global Dynamics Laboratory (CGD) and Computational & Information Systems Laboratory (CISL) at National Center for Atmospheric Research (NCAR) as an Advanced Study Program (ASP) Postdoctoral Fellow later this year. His work focuses on computer simulation, modeling, and spatiotemporal analysis of (1) urban climate and environment, and (2) air quality and aerosol properties. Dr. Zheng is passionate about learning and solving practical problems using Data Science (DS), Artificial Intelligence (AI), Cloud Computing, and High-Performance Computing (HPC).

Appendix D: Collaboratively Generated Urban Reading List

Allen-Dumas, Melissa R., Amy N. Rose, Joshua R. New, Olufemi A. Omitaomu, Jiangye Yuan, Marcia L. Branstetter, Linda M. Sylvester, et al. 2020. “Impacts of the Morphology of New Neighborhoods on Microclimate and Building Energy.” *Renewable and Sustainable Energy Reviews* 133 (November): 110030. https://doi.org/10.1016/j.rser.2020.110030.

Anguelovski, Isabelle, Anna Livia Brand, James J. T. Connolly, Esteve Corbera, Panagiota Kotsila, Justin Steil, Melissa Garcia-Lamarca, et al. 2020. “Expanding the Boundaries of Justice in Urban Greening Scholarship: Toward an Emancipatory, Antisubordination, Intersectional, and Relational Approach.” *Annals of the American Association of Geographers* 110 (6): 1743–69. https://doi.org/10.1080/24694452.2020.1740579.

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